Uncertainty in Measurement

5XTC0 COMPONENTS IN WIRELESS TECHNOLOGY

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Goal

- What is measurement, uncertainty and metrology?
- How to use **applied statistics?**
- How to **determine** an uncertainty **budget?**

Metrology and measurement

- What is **Metrology**
- What **measuring instruments** do we use daily?
  - How **accurate** are they and how important is this?
- Are we **making a measurement**?

Measurement: Definition

- Process of **experimentally obtaining** one or more **quantity values** that can reasonably be **attributed to a quantity**

- The quantity to be measured is also called the **measurand**

https://en.wikipedia.org/wiki/International_Bureau_of_Weights_and_Measures

Measurement: Quantity or measurand

- **Property** of a phenomenon, body, or substance where the property has a **magnitude** that can be expressed as a **number and a reference**

https://en.wikipedia.org/wiki/International_Bureau_of_Weights_and_Measures

Measurement: Reference

1. Measurement **unit**
2. Measurement **procedure**
3. Reference **material**

Combination of such

Entity	Base Unit Name	Abbreviation
Mass	kilogram	kg
Length	meter	m
Time	second	s
Amount of matter	mole	mol
Electric current	ampere	A
Luminosity	candella	Cd
Temperature	kelvin	k

https://en.wikipedia.org/wiki/International_Bureau_of_Weights_and_Measures

Measurement: Result I

- **Quantity values** provided by the measurement are therefore a magnitude and a reference expressing the magnitude of a quantity
- True value
- Uncertainty

https://en.wikipedia.org/wiki/International_Bureau_of_Weights_and_Measures

Measurement: Result II

- Set of quantity values being attributed to a measurand together with **any other available relevant information** ….

https://en.wikipedia.org/wiki/International_Bureau_of_Weights_and_Measures

Measurement: Uncertainty

uncertainty is **doubt**

Uncertainty of measurement is …

Uncertainty **budget**

	Error Source	Primary Evaluation Method
1	Probe relative pattern	Analysis
2	Probe polarization ratio	Analysis
3	Probe gain measurement	Analysis
4	Probe alignment error	Analysis
5	Normalization constant	Analysis
6	Impedance mismatch	Analysis
7	AUT alignment error	Analysis
8	Data point spacing	Measurement
9	Meas. area truncation	Measurement
10	Probe *x*, *y*-position errors	Analysis
11	Probe *z*-position errors	Analysis
12	Multiple reflections (probe/AUT)	Measurement
13	Receiver amplitude nonlinearity	Measurement
14	System phase error due to:	
	Flexing cables/rotary joints	Measurement
	Temperature effects	Measurement
	Receiver phase errors	Simulation
15	Receiver dynamic range	Measurement
16	Room scattering	Measurement
17	Leakage and crosstalk	Measurement
18	Random errors in amplitude/phase	Measurement

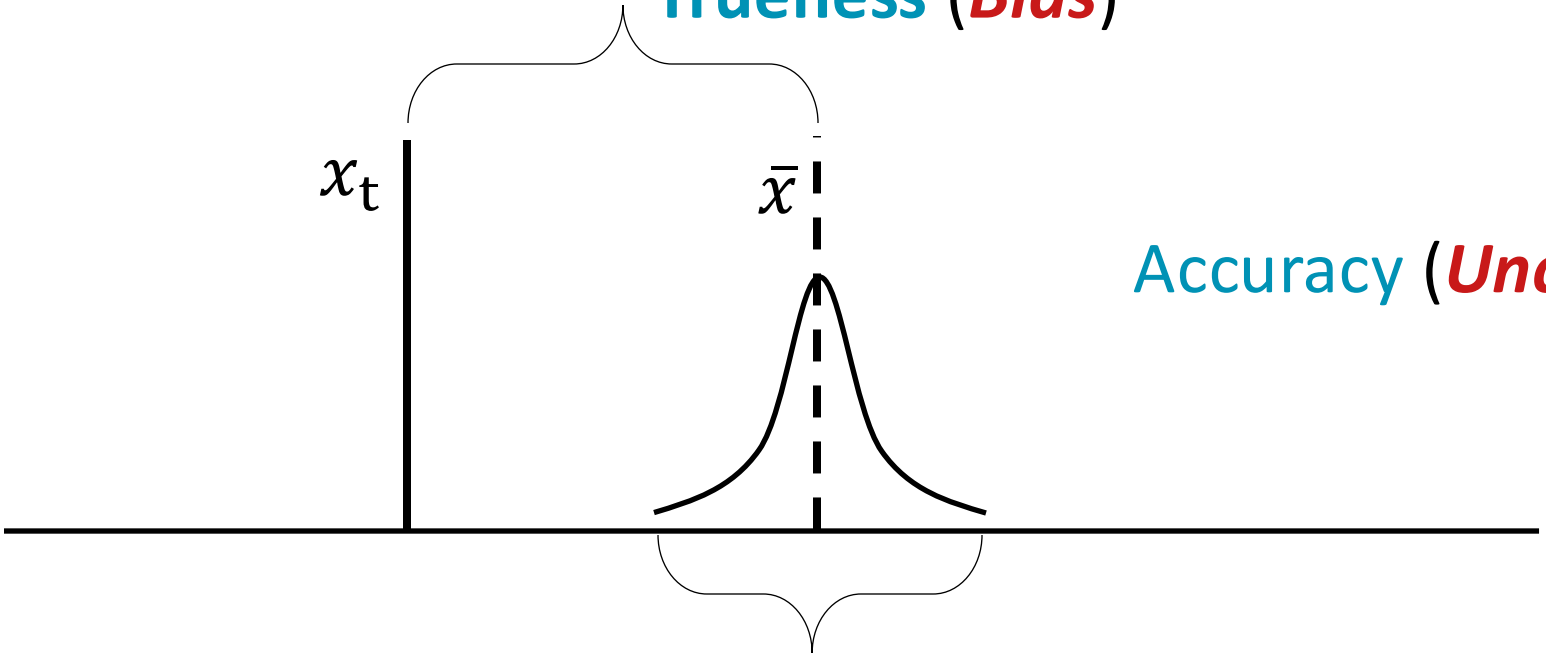
https://www.nsi-mi.com/-/media/project/oneweb/oneweb/nsi/files/technical-papers/2009/identifying-pointing-errors-for-the-nist-18-term-error-technique.pdf?la=en&revision=f62e1379-2de3-438c-822d-4bf3ef7f25c3&hash=0AEFF665550A1E6B6DAC058C8DC2D6BA

Statistics: Error relation table

Type of errors	*Qualitative Performance*	*Quantitative Performance*
Systematic	**Trueness**	Bias
Total	**Accuracy**	Uncertainty
Random	**Precision**	Standard Deviation

Statistics: Error relation table illustration

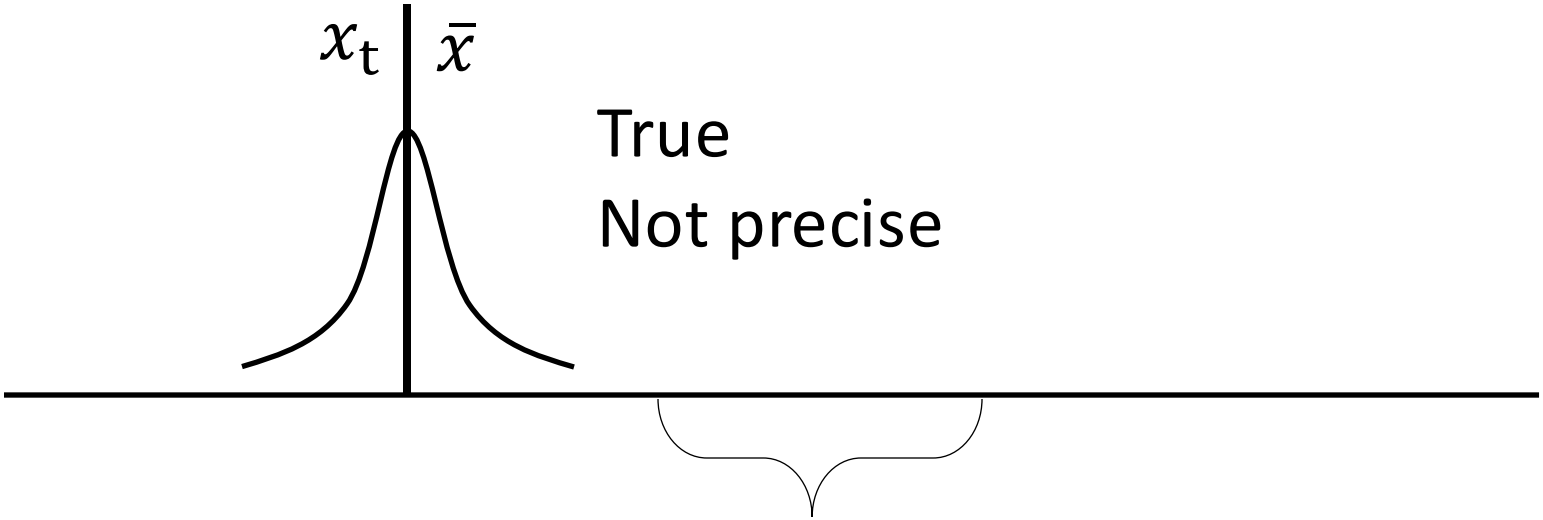
Trueness (*Bias*)



Accuracy (***Uncertainty***)

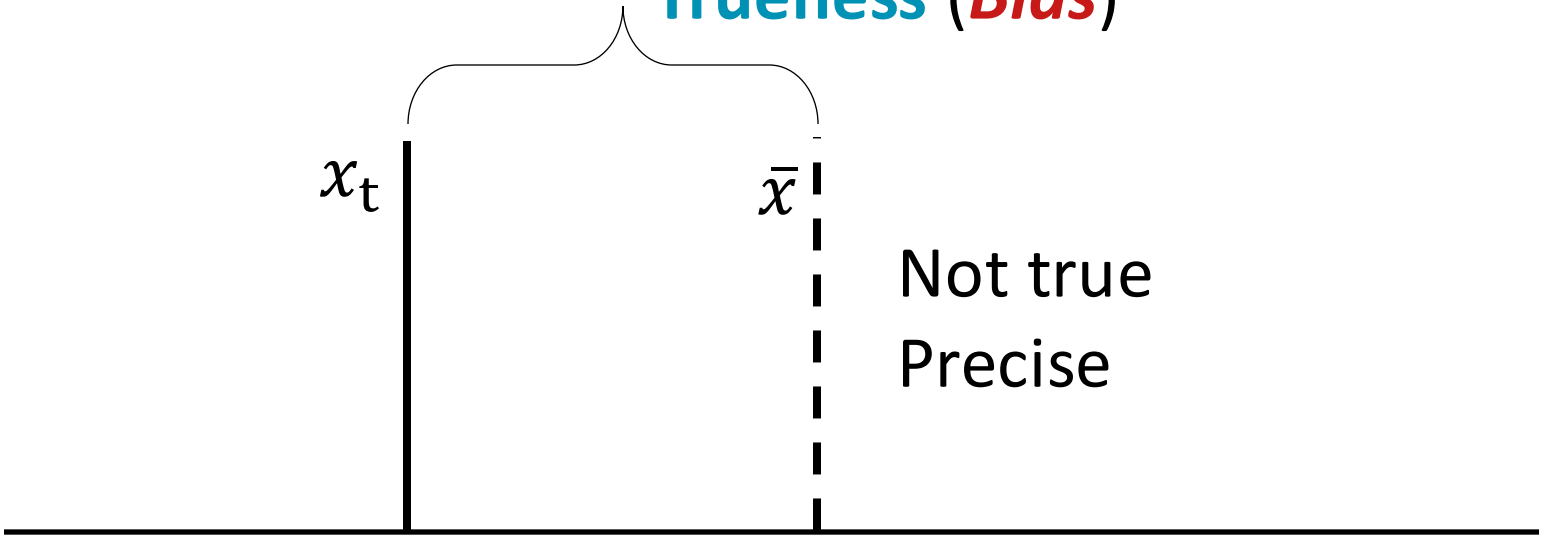
Precision (*Standard deviation of x*)

Statistics: Error relation table illustration

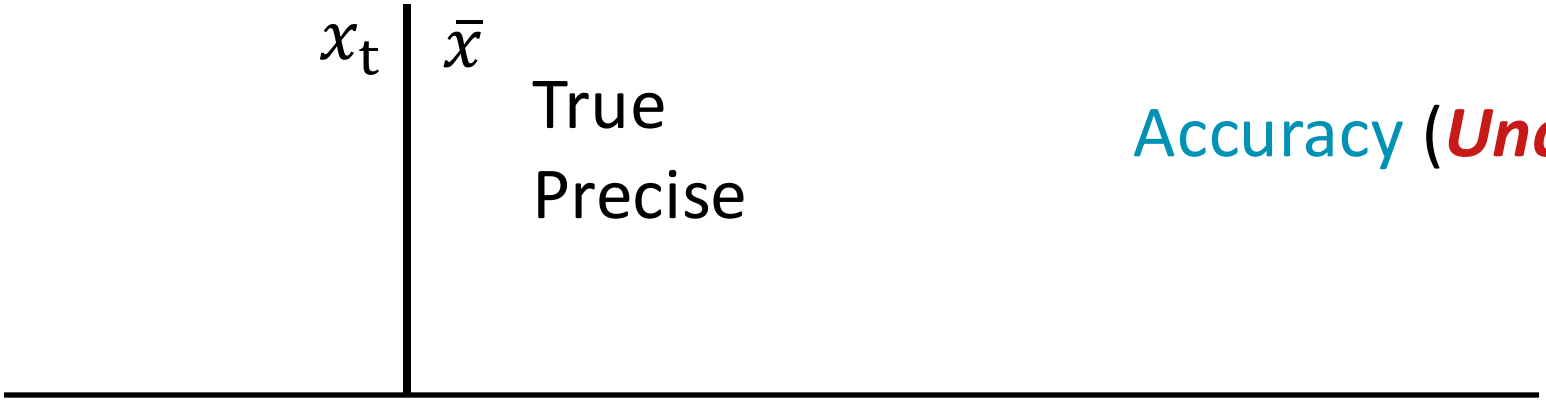


Precision (***Standard deviation of x***)

Statistics: Error relation table illustration



Statistics: Error relation table illustration



Accuracy (***Uncertainty***)

Statistics: Definition

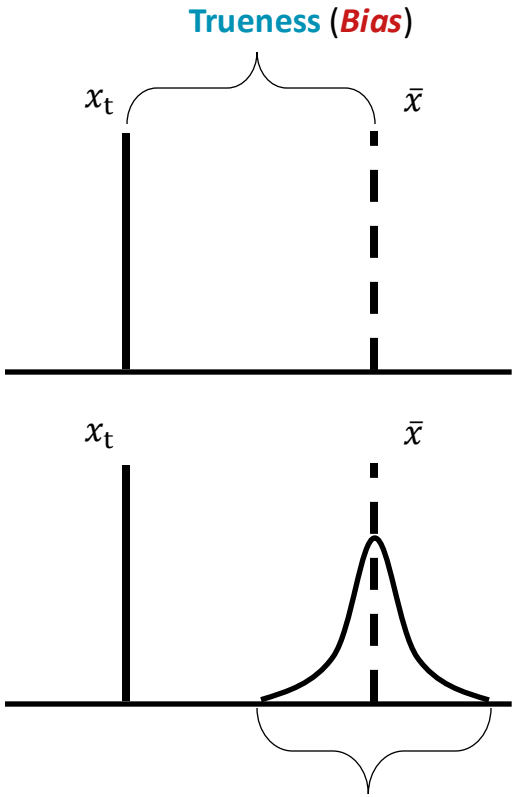
- *"If your experiments **need statistics**, you ought to perform a **better experiment**"* Lord Ernest Rutherford 1871-1937
- What is statistics?
- *"Statistics is a **branch of mathematics** dealing with the collection, analysis, interpretation, presentation, and organization of **data**"*

Statistics: Equations

$$T_{\mathrm{Bias}} = \left(\frac{|R_{\mathrm{v}}|}{|R_{\mathrm{v}} - M_{\mathrm{v}}| + |R_{\mathrm{v}}|} \right) 100\%,$$

$$\sigma = \sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{n}=1}^{\mathrm{N}} (x_{\mathrm{n}} - \mu)^2},$$

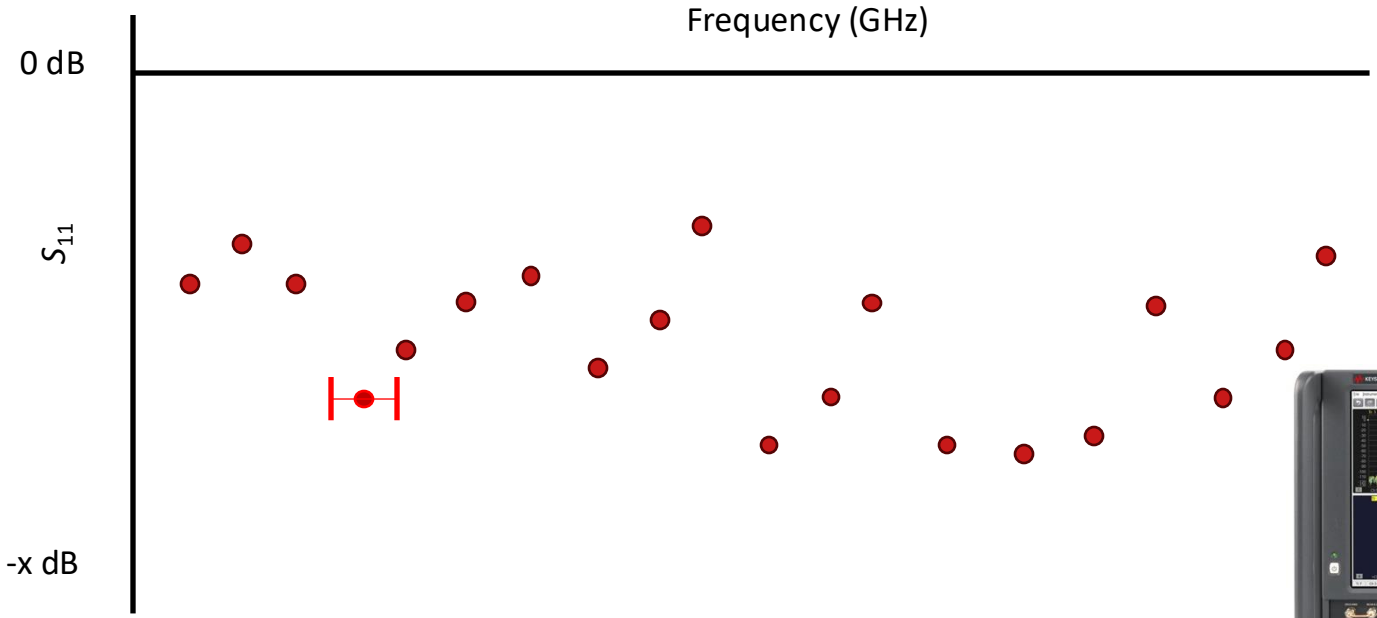
$$s = \sqrt{\frac{1}{\mathrm{N}-1} \sum_{\mathrm{n}=1}^{\mathrm{N}} (x_{\mathrm{n}} - \bar{x})^2}.$$



Vector Network Analyzer: Settings

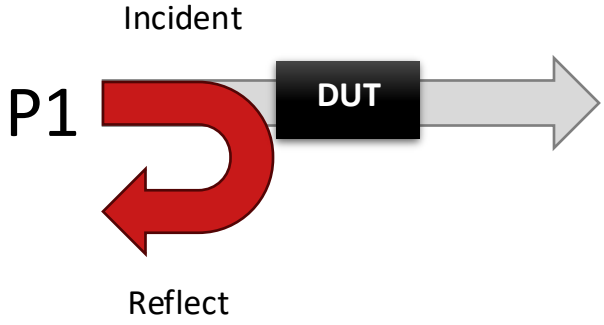
- Frequency
- Power
- Intermediate Frequency Bandwidth (IFBW)
- S_{xx}

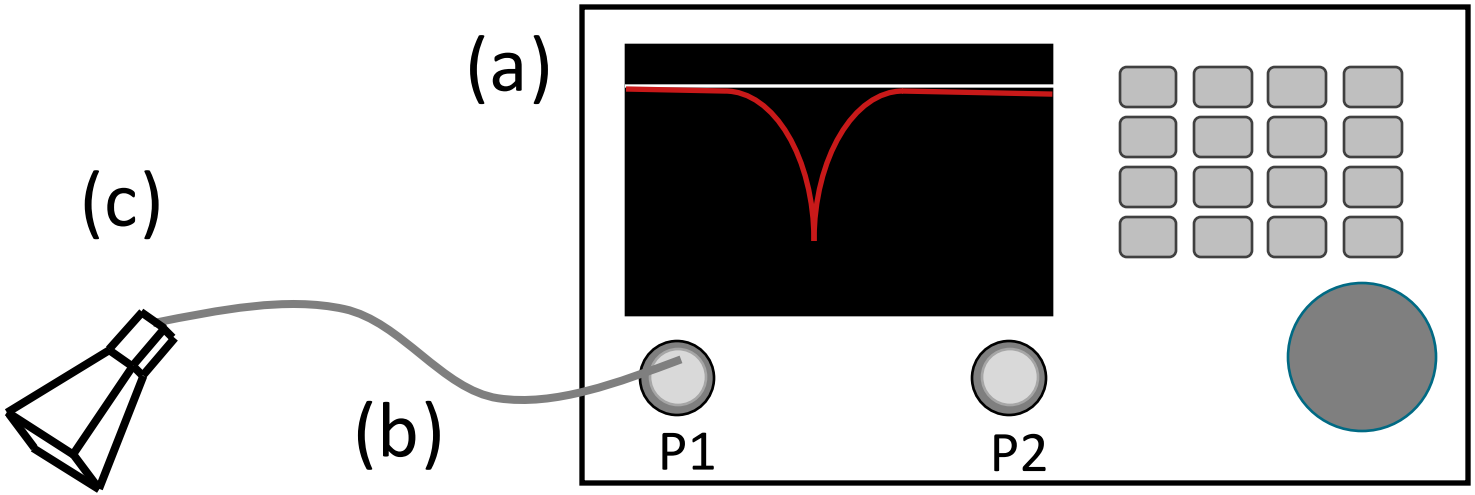
Vector Network Analyzer: Settings



Vector Network Analyzer: S_{11}

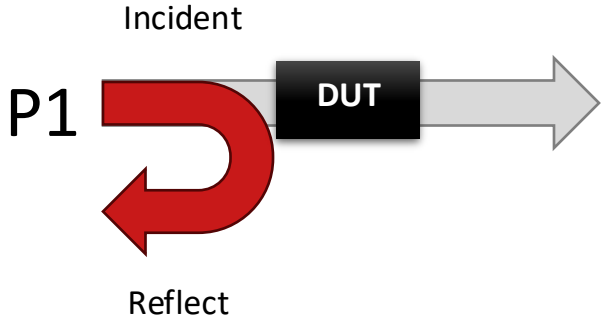
Reflection coefficient





Vector Network Analyzer: S_{11}

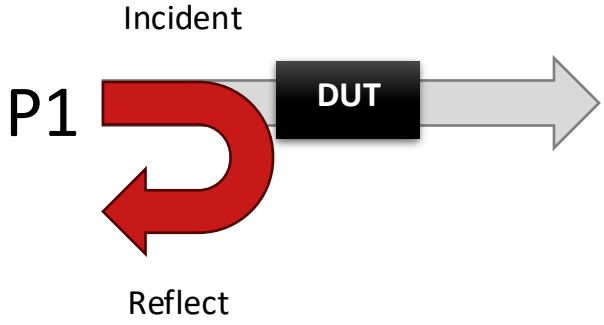
Theory

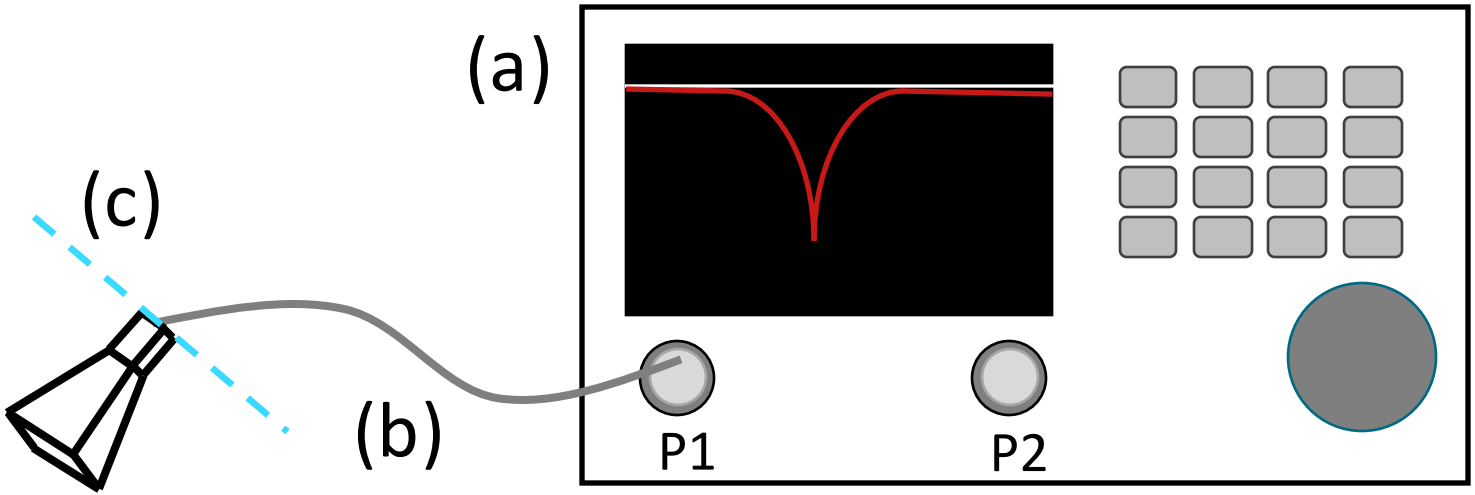


- Ratio between incident and reflected signal
  - Reflection coefficient (Γ)
  - return loss (RL)
  - Voltage standing wave ration (VSWR)

Vector Network Analyzer: S_{11}

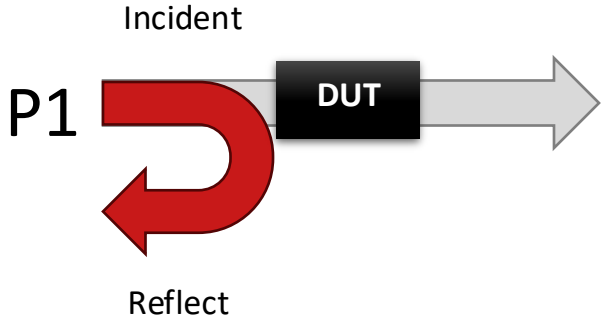
Calibration I

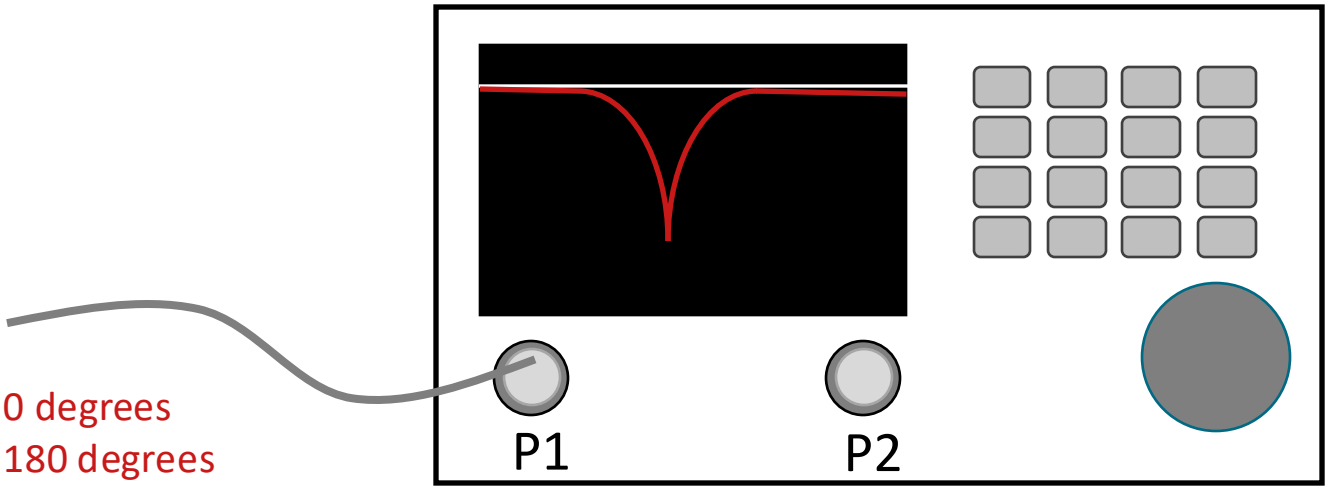




Vector Network Analyzer: S_{11}

Calibration II

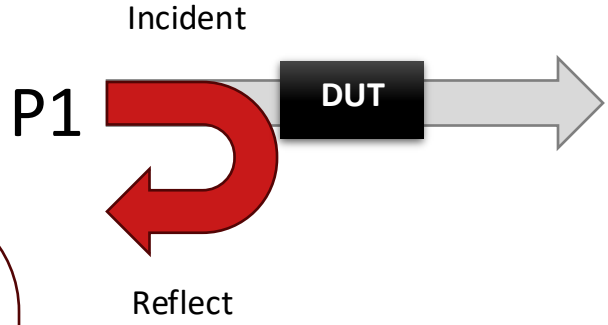


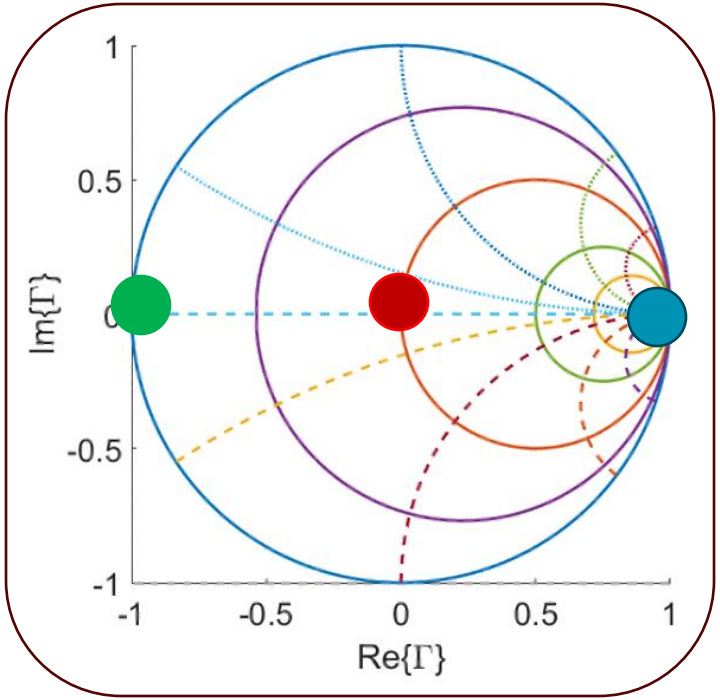


Open = 0 degrees
Short = 180 degrees
Load = 50 Ohm

Vector Network Analyzer: S_{11}

Calibration III

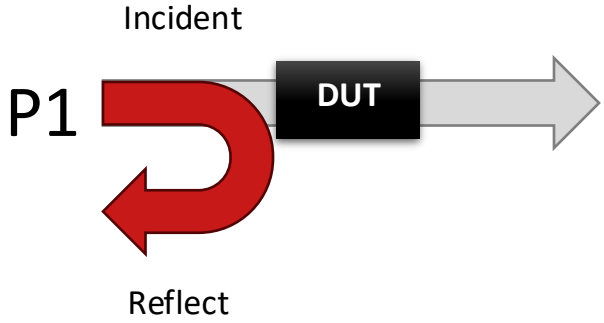




Open = 0 degrees
Short = 180 degrees
Load = 50 Ohm

Vector Network Analyzer: S_{11}

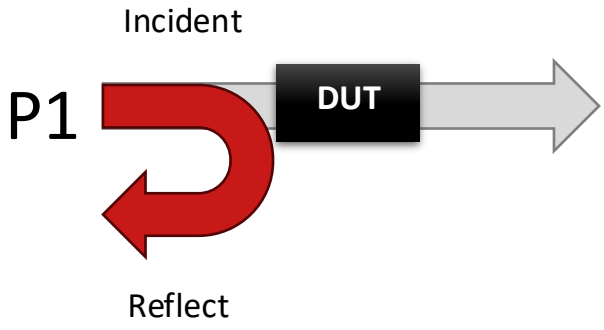
Measurement

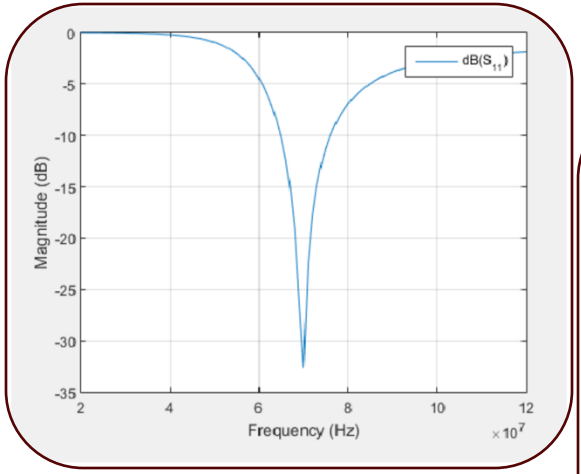


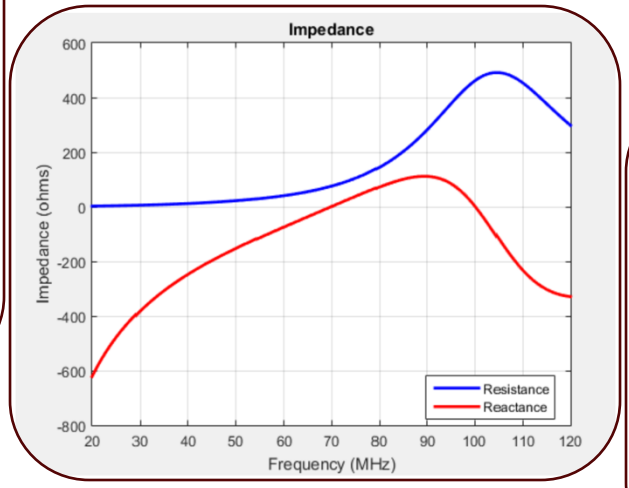
- Reflection coefficient [S_{11} (Γ)]:
  - Impedance match / mismatch
  - Part of realized gain
  - How much power is transferred to a load e.g. antenna

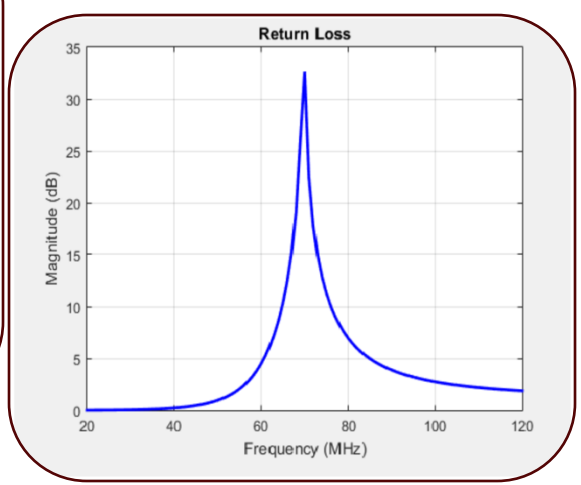
Vector Network Analyzer: S_{11}

Representation



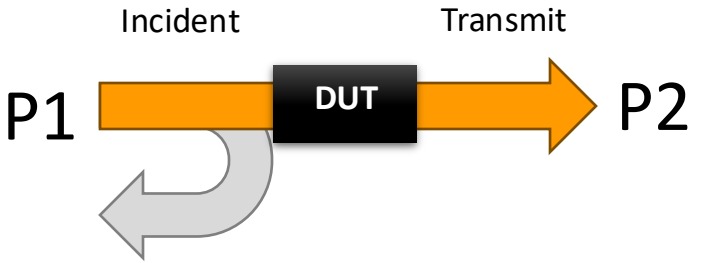






Vector Network Analyzer: S_{21}

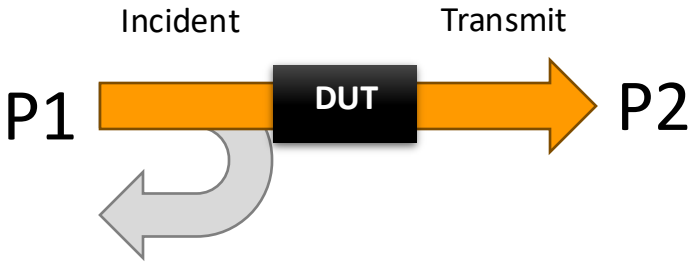
Transmission coefficient

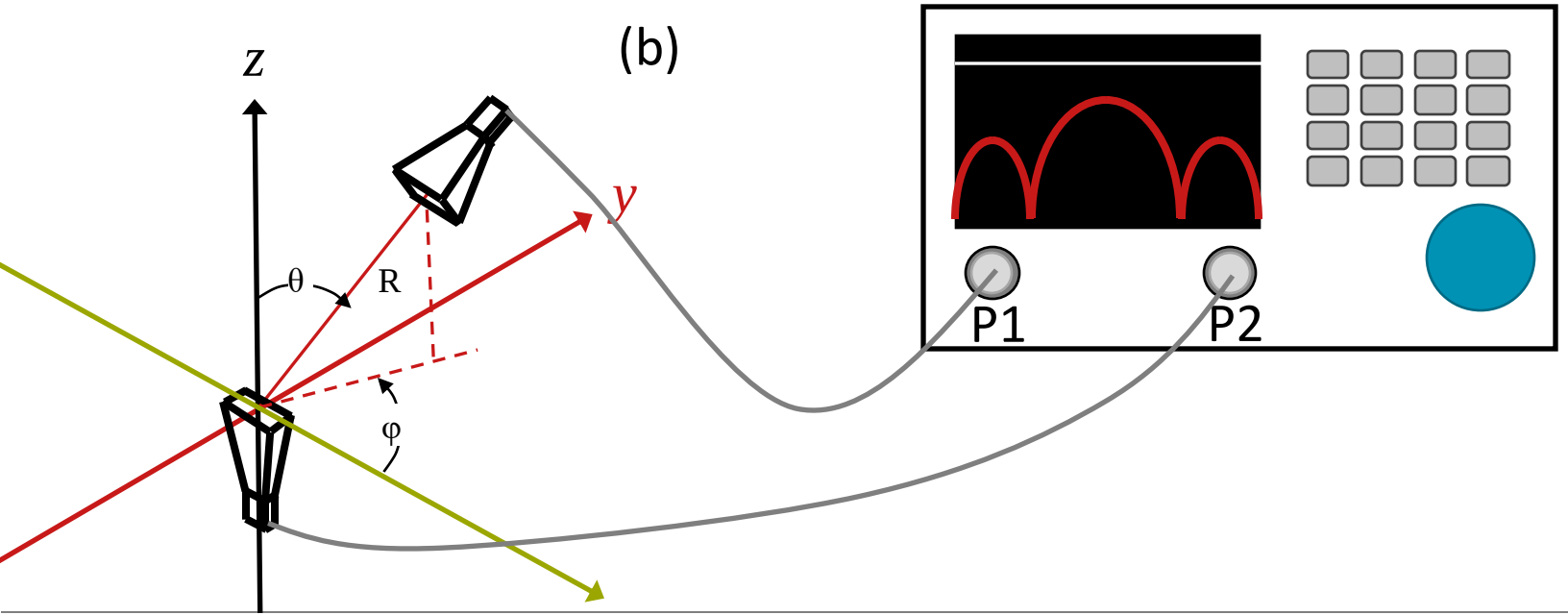


- Reflection coefficient [S_{11} (Γ)]:
  - Impedance match / mismatch
  - Part of realized gain
  - How much power is transferred to a load e.g. antenna

Vector Network Analyzer: S_{21}

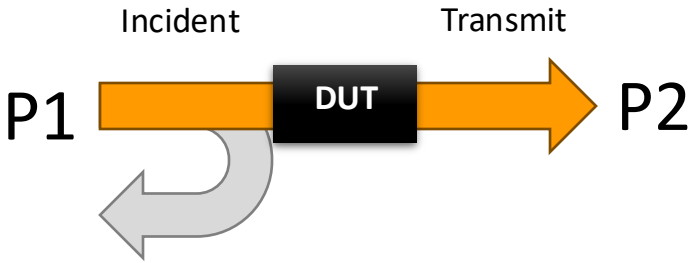
Coordinate system

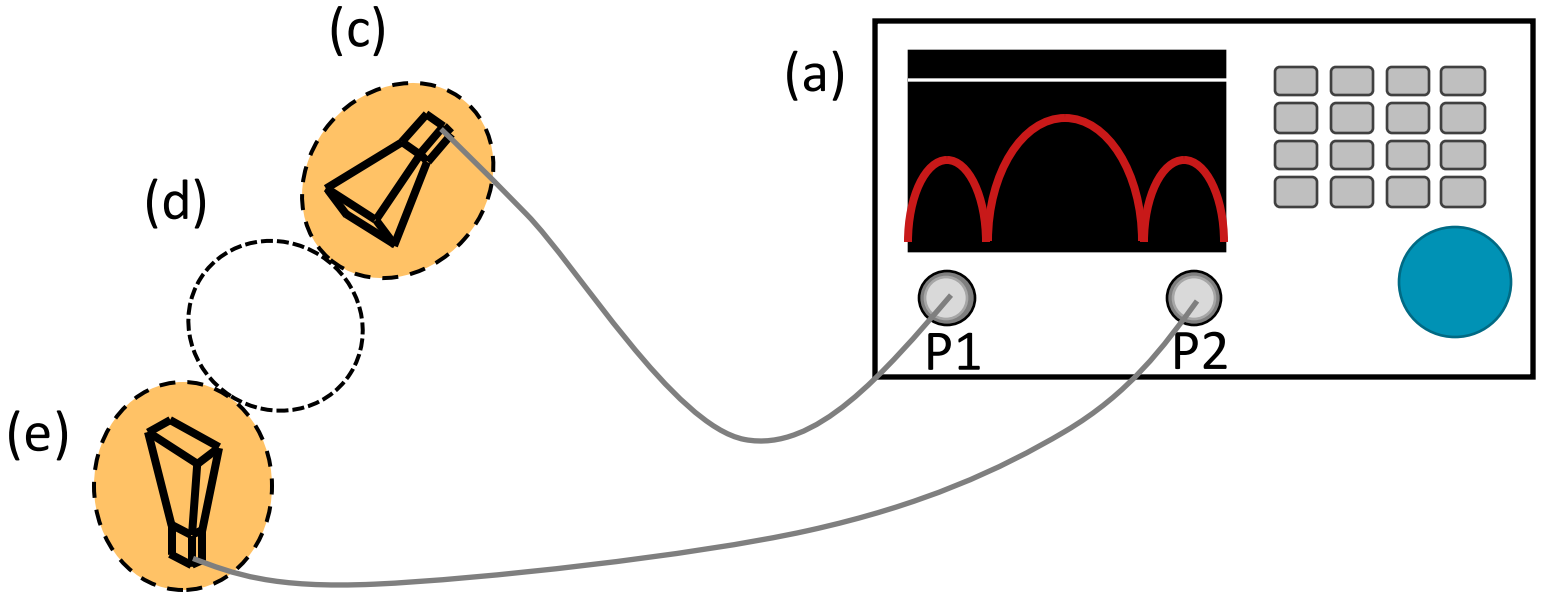




Vector Network Analyzer: S_{21}

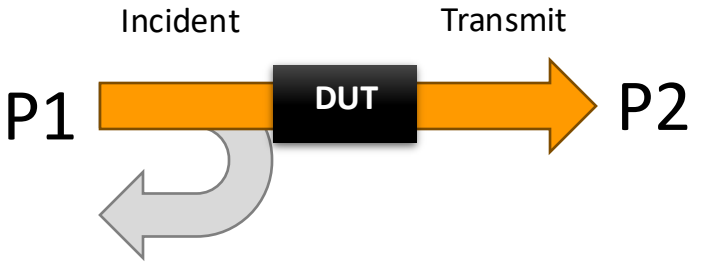
Near- and far-field





Vector Network Analyzer: S_{21}

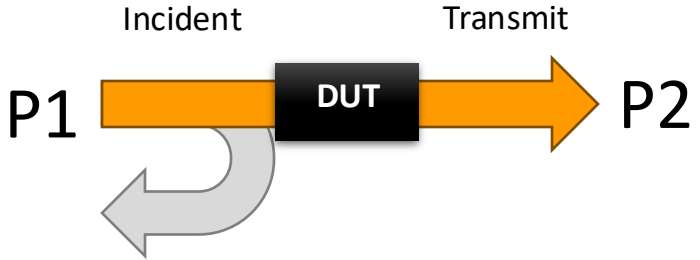
Measurement

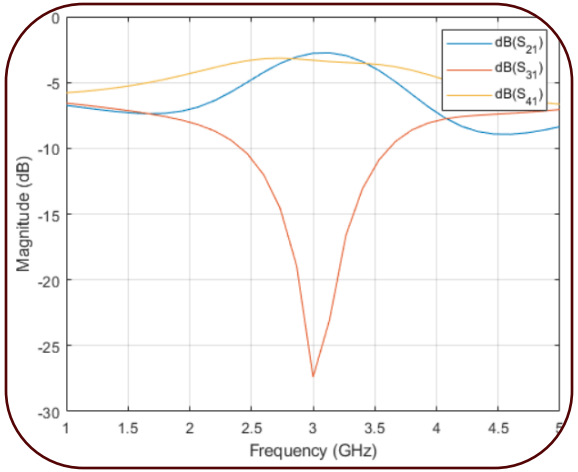


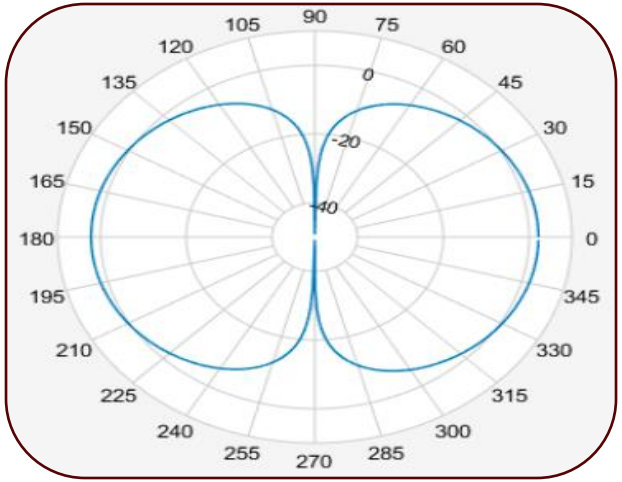
- Transmission coefficient [S_{21} (T)]
  - Radiation pattern [S_{21} (ϕ)]
  - **Gain, realized gain (G)**
  - Efficiency (η)
  - Total radiated power (TRP)
  - Equivalent isotropic radiated power (EIRP)

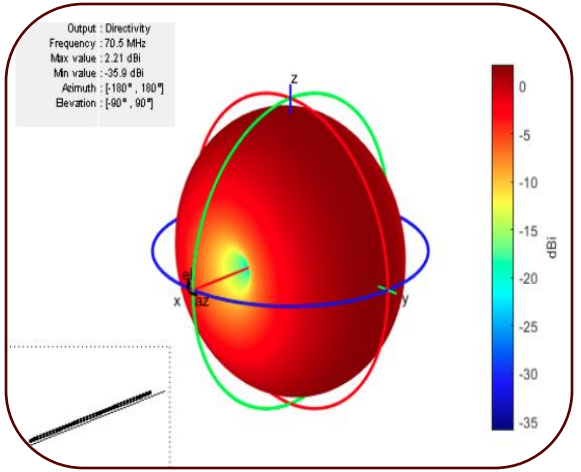
Vector Network Analyzer: S_{21}

Representation









Statistics

Evaluation type

- **Type A** evaluation
  - *method of evaluation of uncertainty by the statistical analysis of series of observations*
- **Type B** evaluation
  - *method of evaluation of uncertainty* ***by means other than the statistical analysis of series of observations***

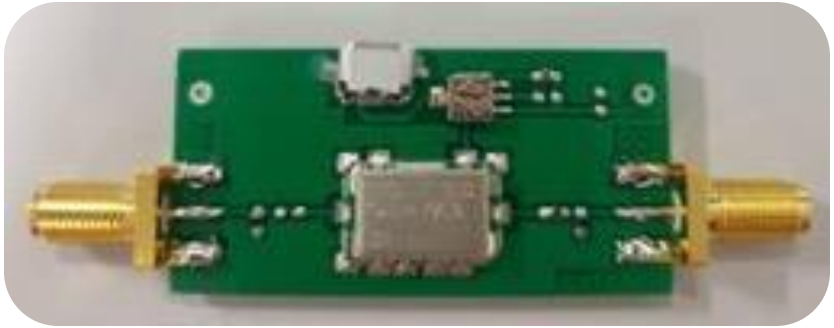
Statistics

Obtaining data

- Repeatability:
  - *Closeness of the agreement between the **results of successive measurements of the same measurand** carried out under the **same conditions** of measurement*
- Reproducibility:
  - *Closeness of the agreement between the **results of measurements of the same measurand carried** out under **changed conditions** of measurement.*

Uncertainty

Budget example I, amplifier



- Calibration
- RF-cable reconnect
- DC-power supply
- Different PCB boards with the same function

Uncertainty

Budget example II, antenna and stub

- Calibration
- RF-cable reconnect
- Antenna alignment
- Environment

Uncertainty

Applying …..

1. Chose number of repeated measurements (N) and derive degrees of freedom (N-1)
2. Standard uncertainty
3. Combine the measured uncertainties (RMS)
4. Expand the number (*k*)

Uncertainty

T-table

Degrees of freedom	Fraction P in percent					
v	68.27	90.00	95.00	95.45	99.00	99.73
1	1.84	6.31	12.71	13.97	63.66	235.80
2	1.32	2.92	4.30	4.53	9.92	19.21
3	1.20	2.35	3.18	3.31	5.84	9.22
4	1.14	2.13	2.78	2.87	4.60	6.62
5	1.11	2.02	2.57	2.65	4.03	5.51
6	1.09	1.94	2.45	2.52	3.71	4.90
7	1.08	1.89	2.36	2.43	3.50	4.53
8	1.07	1.86	2.31	2.37	3.36	4.28
9	1.06	1.83	2.26	2.32	3.25	4.09
10	1.05	1.81	2.23	2.28	3.17	3.96
...	...	...	...	...	...	...
20	1.03	1.72	2.09	2.13	2.85	3.42
...	...	...	...	...	...	...
30	1.02	1.70	2.04	2.09	2.75	3.27
...	...	...	...	...	...	...
40	1.01	1.68	2.02	2.06	2.70	3.20
...	...	...	...	...	...	...
50	1.01	1.68	2.01	2.05	2.68	3.16
100	1.005	1.660	1.984	2.025	2.626	3.077
∞	1.000	1.645	1.960	2.000	2.576	3.000

Thank you